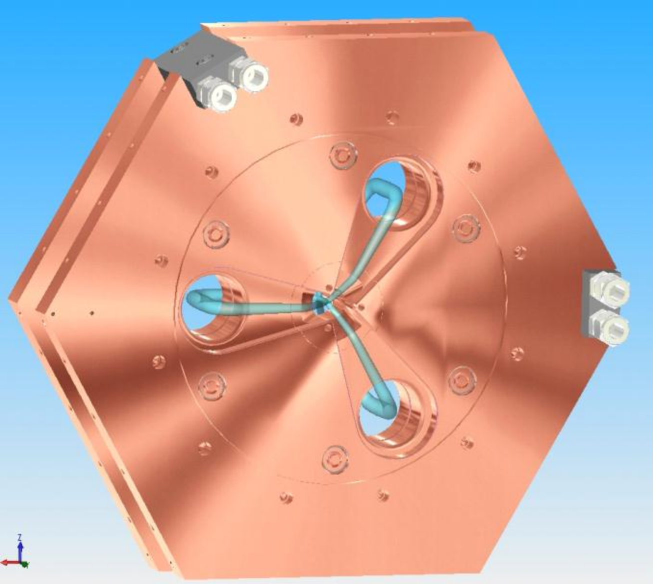

ENERGETIQ

High Brightness Xenon Z-pinch for EUV Metrology (?)

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Background

- The EQ-10 electrodeless z-pinch has been successful from both an engineering and market perspective.
  - 20? Sources in the field
  - Physics and engineering (thermal, electrical) aspects well understood
  - Process parameter space (voltage, pressure) well explored
  - More basic parameters (pinch geometry, current temporal trajectory) not so well explored.
    - Each experiment requires significant mechanical or electrical modification of the hardware
- Currently, best brightness B ~ 8 (W/mm^2-sr)
- Can we scale the EQ-10 to a brightness of 100? What would such a source look like?

Increase the pulse rate; reduce plasma size

- The standard EQ-10 runs at ~2000 Hz, (0.5 msec period) with an EUV pulse of about 100 nsec, or a duty cycle of less than 0.02%.
- We have run the EQ-10 architecture (with modifications) up to 10 KhZ
- If we guessed that we might need a 50 kHz rate, we would still be at only a 0.5% duty cycle.
  - Power system topology must change – can't use magnetic switching!
- We have to keep the plasma small. At brightness of 100, power requirements quickly become unreasonable as plasma size increases.
- Is this a path to a high brightness source?

Goal:

- **Parameters for a High Brightness Source to meet Mask Inspection Requirements of**
    - 100W/mm^2/sr
    - ~5 W /2pi in 2%bw at 13.5nm
    - Excellent Spatial Stability
    - Excellent Pulse-to-pulse repeatability
    - Reliability and low cost of ownership

Strategy:

- Given demonstrated performance of EQ-10 – existing data
- Plus previously validated models (physics, electronic)
  - Consistent with existing data
- Plus requirements for new source
  - Brightness, power, plasma geometry
- Develop specifications for new device
  - Pulse rate, plasma geometry
  - Electrical parameters
    - Required current, voltage, timing
- Generate requirements for source geometry, thermal design, modulator architecture

Key assumptions – Plasma parameters

- **Need Te ~ 25 ev**
- **Z=10 (roughly)**
- **Density similar or higher (2x) compared to EQ10**

we must get to the same (dimensionless) optical thickness as EQ-10, so can reduce length of plasma without loosing brightness!

- EQ-10 data shows we have already achieved similar optical thickness in 3 mm long and 12 mm long plasmas.

Baseline for Scaling – short, dense plasma

- Our highest brightness plasmas (bore 13 mm long by 6 mm diameter) gave 8 w/mm^2-sr. Plasma was 12 mm long x 0.4 mm diameter
- A 3 mm long x 6 mm diameter bore gave much shorter plasma (3 mm) with brightness 4.5, density ~ 2x the previous case
- Length was reduced 4x; brightness only 2x.
- Plasma diameter remained ~ 0.4 mm
- We choose the 3 mm x 6 mm bore condition as a baseline for the scaling exercise

Scaling procedure -- determine required current

- Given achieved, required brightness (4.5,100) sets pulse rate (~ 55 kHz)
- Given achieved, required plasma diameter sets bore diameter (6mm,1mm)
- Scale bore length from 3mm to 2mm
- Assume higher density will be required (conservative, 2x)
- Otherwise plasma parameters assumed identical (electron temperature Te ~25 eV, charge state Z ~10 – yields plasma pressure.
- Scale current requirement via Bennet criterion

$$\mu_0 I^2 = 8\pi N k_B T \ ,$$

  - Balance plasma versus magnetic pressure; compare to base plasma.

Peak current calculation

Pulse rate: scaled to achieve goal. (~ 20x)

Bore geometry: scaling: 1 mm bore diameter plus compression ratio gives plasma size goal. Modest length decrease.

Plasma density: choose to double to ensure optical thickness. (Scaling implies 1.5x sufficient)

Plasma Charge state – for Xenon, must be ~10 times ionized to radiate in EUV.

Electron temperature – from charge state; weak density dependence. Assume unchanged. (25 eV)

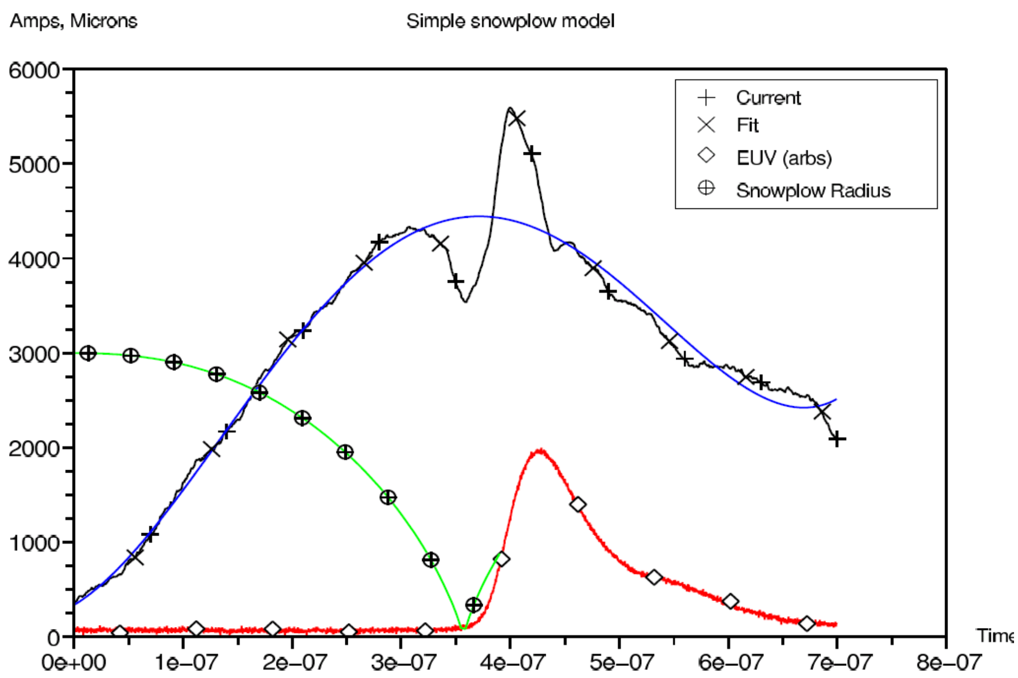
Density, state, radial size give Bennet current.

In base plasma, current peaks above Bennet current. Use same scaling in proposed device.

	Existing	Proposed
Bore diam,mm	6	1
length	3	2
pulse rate	2.50E+03	5.56E+04
Brightness	4.5	100
Compressed diameter	0.4	0.07
Compression ratio	15	15
Uncompressed Ion density (mks)	1.77E+21	3.53E+21
Density(pressure) increase		2.00
Bennet current	6.64E+03	1.56E+03
Peak/Bennet	1.05	1.26E+00
Peak current	6.99E+03	1.98E+03

Dynamics: estimate timescales

- Pinch dynamics well described by snowplow model + other physics



Snowplow - given bore diameter,initial density, current profile – calculates time to pinch.

Alternative approach – dimensional analysis to extract timescale

Dimensional Analysis

$$\Pi = \frac{\mu I_{\max}^2 \tau^2}{4\pi \hat{m} r_0^2} \qquad (2.4)$$

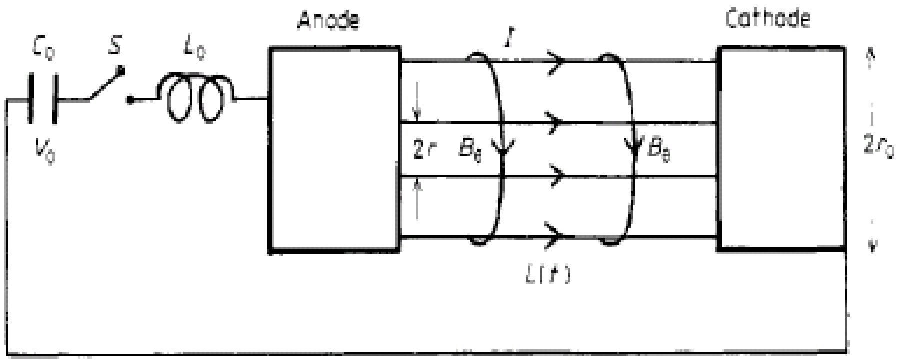
is a dimensionless scaling parameter of the problem. Two implosions with the same functional dependence of current on time [i.e., with the same dependence $\tilde{I} = \tilde{I}(\tilde{t})$] occur in a similar fashion if the parameter Π for them is the same. In particular, the instant in time when the pinch collapses on the axis, measured in units of τ, is the same for both implosions.

All parameters are known except τ, the time to reach peak current. Since we want to scale to a known plasma, we can compute π from our base plasma, and solve for τ for the scaled plasma.

- **D. D. Ryutov, M. S. Derzon, and M. K. Matzen, "The physics of fast Z pinches," *Reviews of Modern Physics*, vol. 72, pp. 167-223, Jan. 2000.**

Further dynamics -- circuit parameters

S. Lee, "An energy-consistent snow-plough model for pinch design," *Journal of Physics D: Applied Physics*, vol. 16, no. 12, pp. 2463-2469, Dec. 1983.



The energy storage capacitors, total inductance (plasma + external), and total resistance form a simple R-L-C circuit. We extract the series inductance L0 and resistance R from measured waveforms, and calculate the plasma inductance. To change L0 significantly requires source redesign; we assume that the external inductance can be reduced by a factor of 2 by reducing overall size.

$$I(t) = \frac{V_0}{\beta L} e^{-at} \sin \beta t$$

$$V_c(t) = V_0 e^{-at} \cos \beta t$$

where:

$$\beta = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

$$a = \frac{R}{2L}$$

Values of Circuit Parameters

Plasma resistance assumed unchanged (conservative).

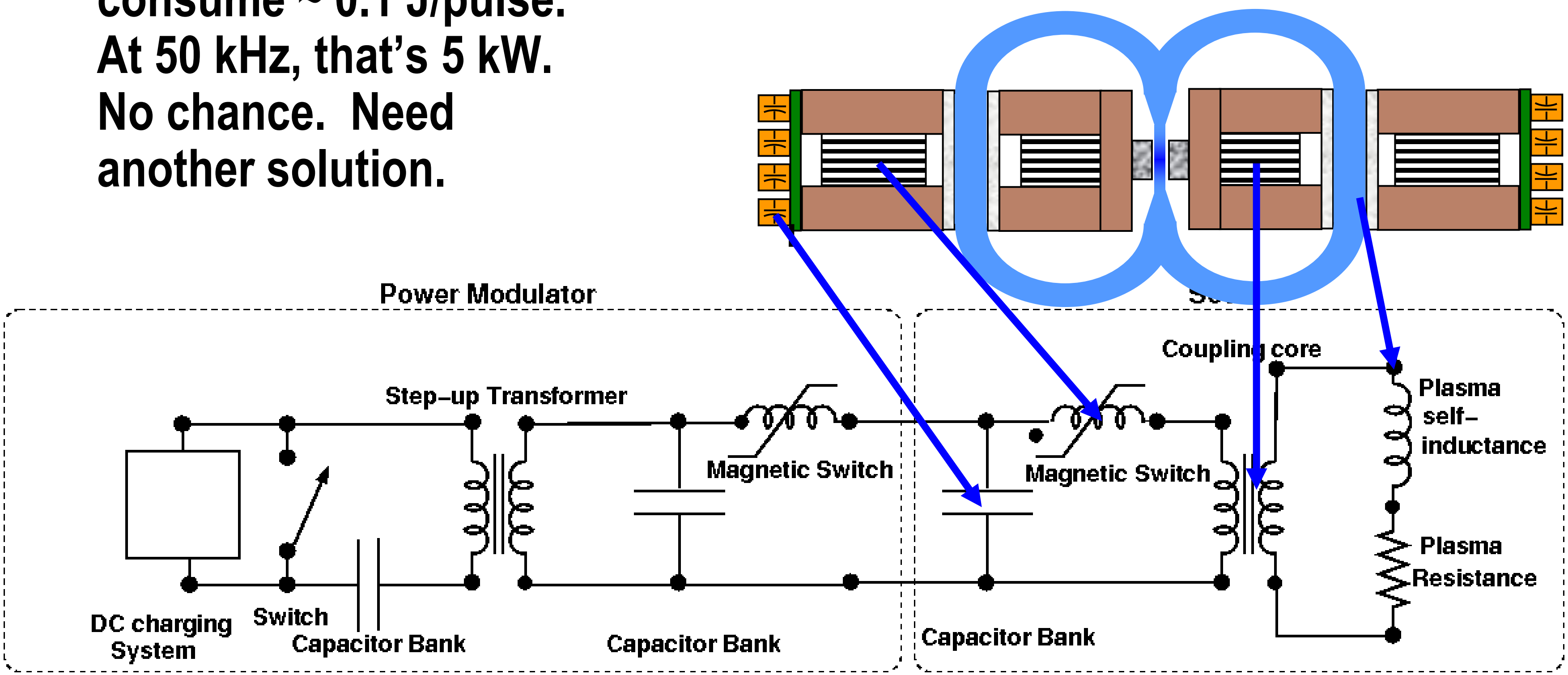
Plasma inductance calculated; external inductance assumed reduced a factor of 2, consistent with mechanical source size reduction.

Circuit equations can be solved to determine required capacitance, voltage, power.

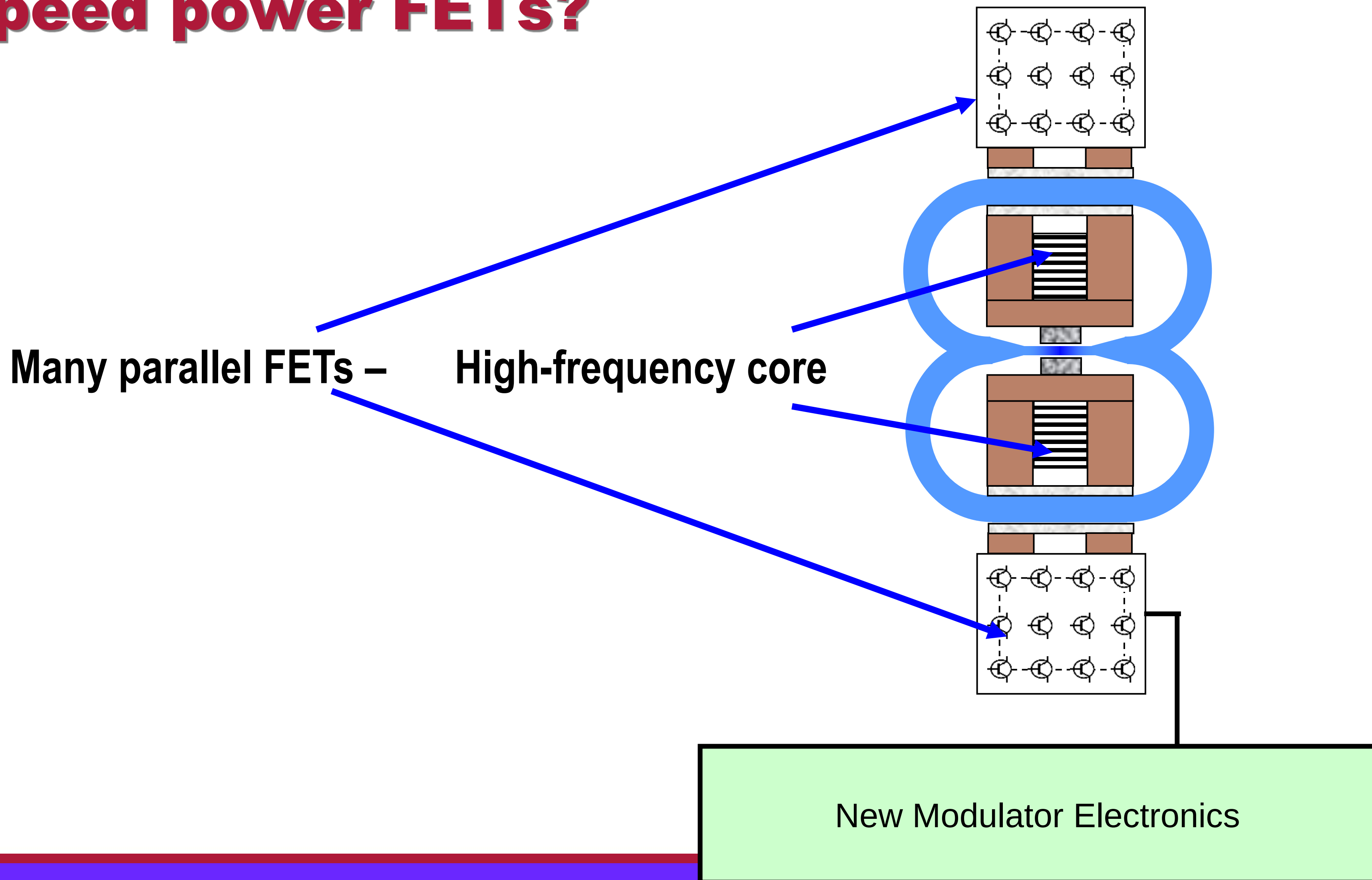
	Existing	Proposed
eq 2.4 scaling param Ryutov	3.11E+00	3.11E+00
Time to reach peak current	2.51E-07	4.18E-08
Total inductance	1.90E-08	9.49E-09
Resistance	9.87E-02	9.87E-02
Capacitance	2.38E-06	8.96E-08
Voltage	-1200	-666
Power to plasma (watts)	4.21E+03	1.66E+03

Can the EQ-10 power architecture manage high frequency?

No. The switch cores consume ~ 0.1 J/pulse. At 50 kHz, that's 5 kW. No chance. Need another solution.

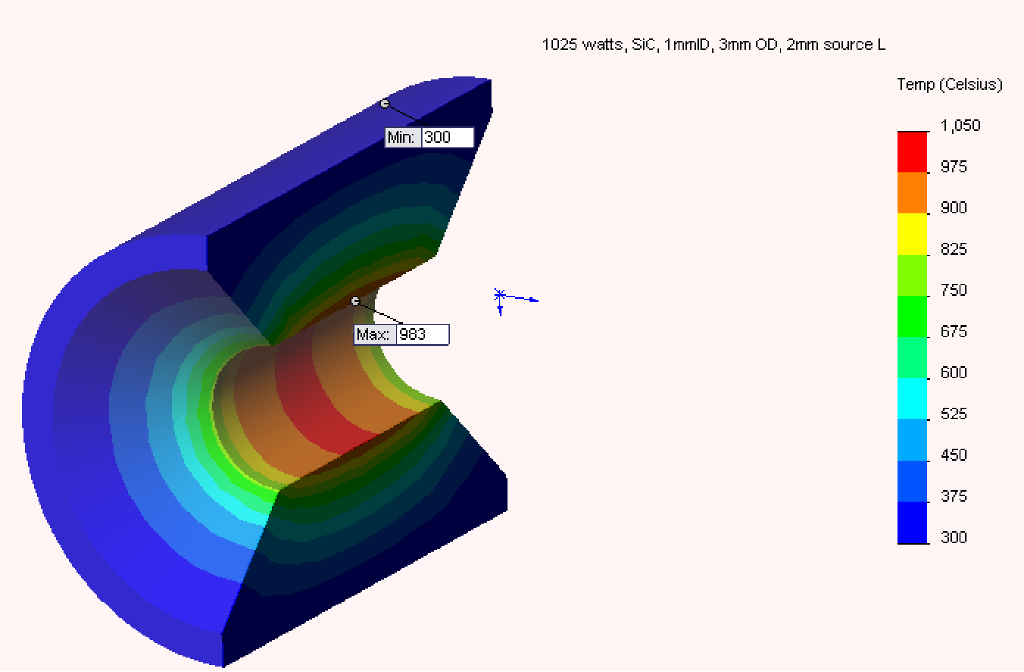


Replace magnetic compression with high-speed power FETs?



Thermal Modeling results

- Assumptions
  - Silicon Carbide bore insert
  - 1mm ID x 2mm L, 3mm OD
  - 1025 W incident on ID 2mm L
  - OD clamped at 300C by copper cooling structure, allowing for 250C gradient in copper to water-cooling (conservative)
- Result
  - Maximum delta temperature - 583K above OD temperature



Estimate bore lifetime due to sputtering

Bore Erosion Calculation

Baseline - existing bore	
Estimated for high-brightness	
Initial Diameter	6
Final Diameter	10.44
Volume Lost, mm^3	1.72E+02
Joules delivered	2.25E+09
mm^3 per Joule	**7.63E-08**
initial diam,mm	1
final diam,mm	1.2
Volume, mm^3	0.69
Joules to remove	9.05E+06
Energy of 1 pulse	2.88E-02
Pulses	3.14E+08
Lifetime,minutes	**1.05E+02**

Single bore has ~ 100 minute lifetime at full pulse rate

~ 20 hrs at 4000-5000 hz for initial tests

Need an automated way to replace bore!

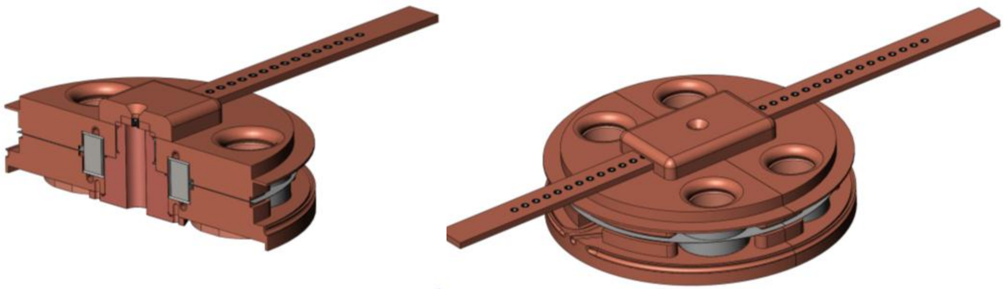
Simple linear carrier -

2.4 mm pitch

150 bores

Total length ~ 360 mm

Total time ~ 10 days/carrier (24/7)



Programmatic aspects (risk reduction)

- Initial work can be done in (nearly) correct geometry, at low(er) frequency, using existing EQ-10 hardware set.
  - What is the real size scaling?
- Further validation using existing hardware, in "burst" mode –
  - We have delivered EQ-10 systems running at 10 KHz continuous
  - Could operate similar hardware at 20 KHz for short periods
  - Key question – can a small high-frequency pinch be adequately fueled?
- Major costs of program can be deferred until technical risks are assessed.

Summary:

- Conceptual design of a small, high-frequency Xenon Z-pinch
  - Based on EQ-10 architecture
  - Goal -- brightness ~ 100 W/mm^2-sr, power ~5 W
- Clearly a high-risk design. Odds of all the physics and engineering working out favorably are not high.
- However, if it could be made to work, it is a very attractive solution.
  - No lasers (windows, mirrors, etc)
  - No tin (or tin remediation)
  - No obviously high-cost components
- Alternatively, maybe this design is a proof that a Xenon solution is impossible?